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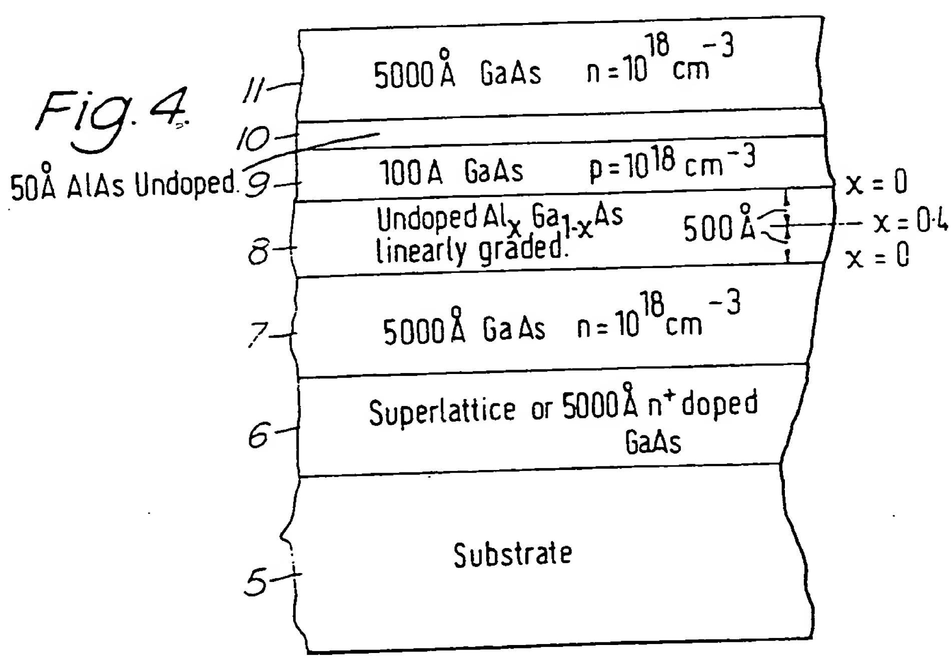
None

(58) Field of search
UK CL (Edition J) H1K KEAA KEE KELX
INT CL⁴ H01L

(54) Semiconductor laser

(57) A tunable laser comprises a first semiconductor structure (7, 8, 9) which exhibits a quantum well with bound states, the energies of which are variable by application of a first voltage between regions of the first structure. Electrons are injected into the quantum well by a second structure (10, 11) in response to a second voltage. Electrons and holes recombine in the quantum well, producing photons having an energy level which is dependent upon the magnitude of the first voltage so that the frequency of operation of the laser is variable by varying the first voltage. The first structure may comprise layers of GaAs of opposite conductivity types with a layer of $A1_xGa_{1-x}As$ therebetween.

Fig. 4



At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy

Fig. 1.

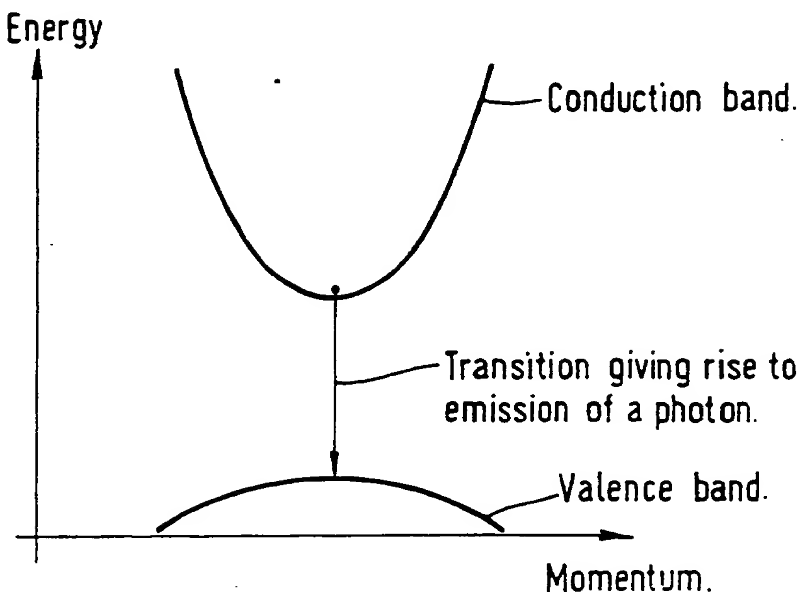


Fig. 2.

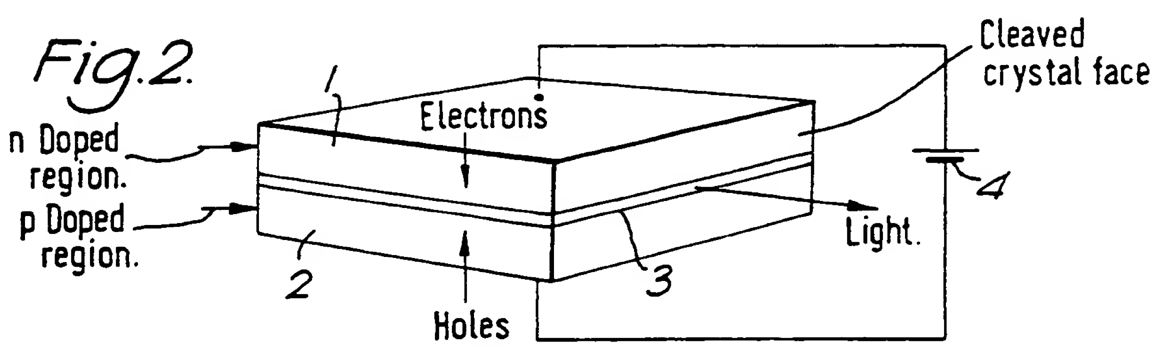


Fig. 3.

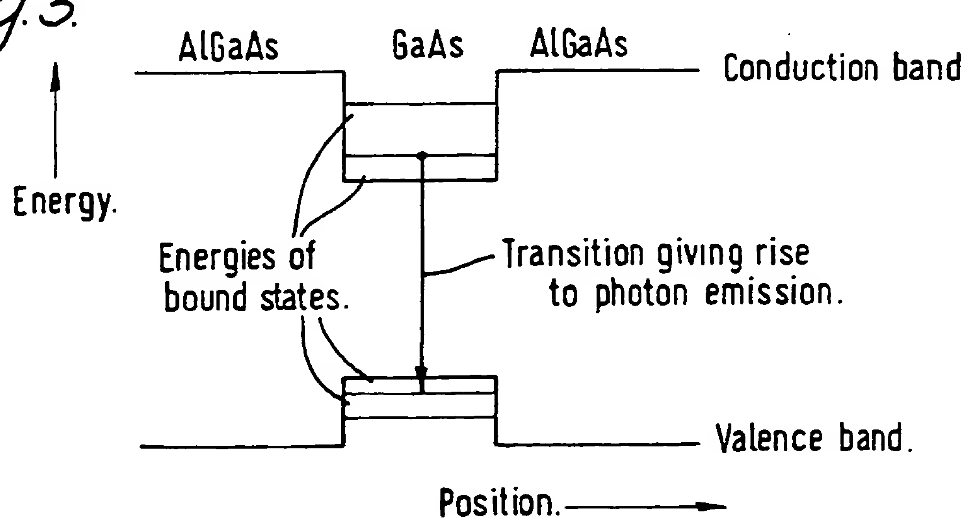
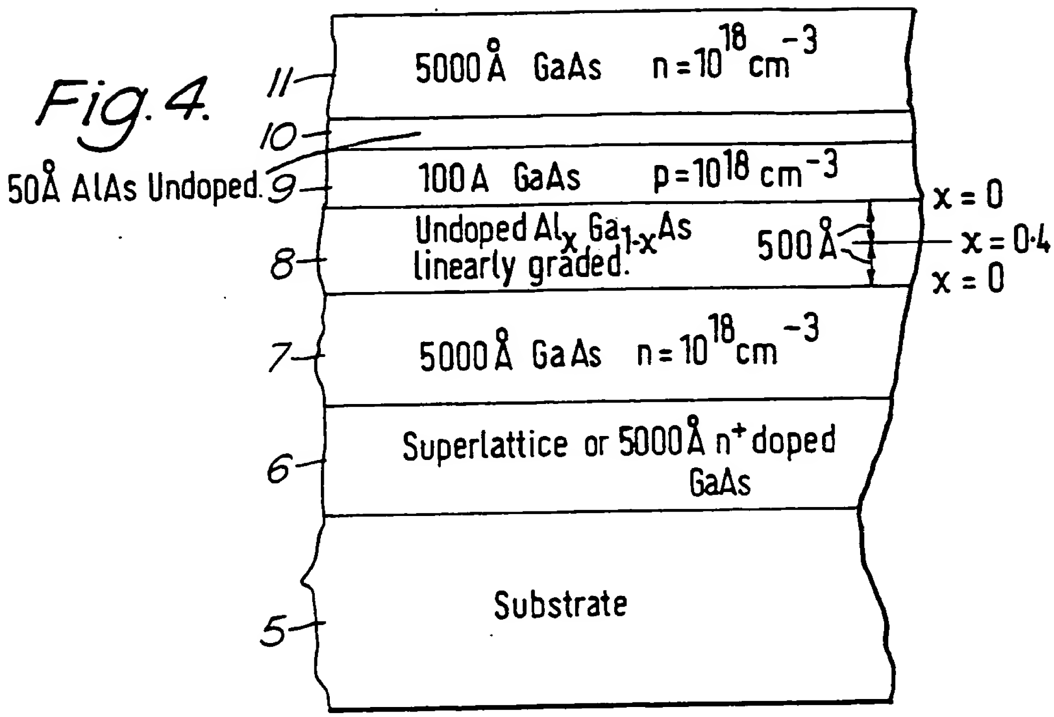
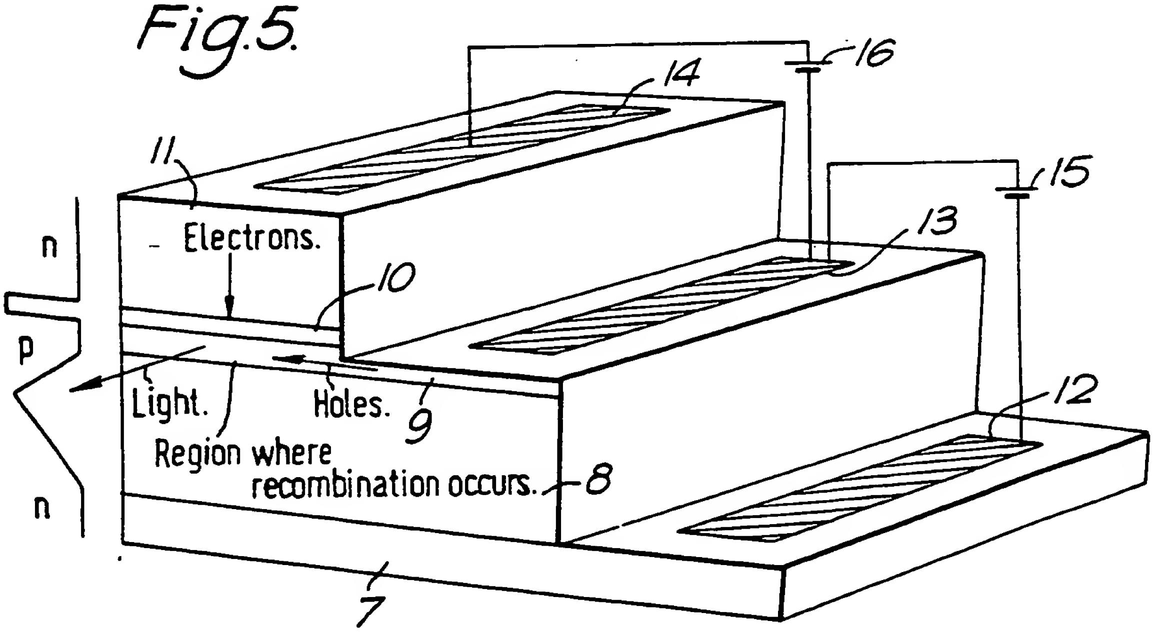


Fig.4.



11
5000Å GaAs n=10^18 cm^-3
10
50Å AlAs Undoped.
9
100A GaAs p=10^18 cm^-3
x = 0
8
Undoped Al_x Ga_1-x As linearly graded.
500Å
x = 0·4
x = 0
7
5000Å GaAs n=10^18 cm^-3
6
Superlattice or 5000Å n+ doped GaAs
5
Substrate

Fig.5.



16
14
11
15
13
n
Electrons.
10
p
Light.
Holes.
9
12
Region where recombination occurs.
8
n
7

Fig. 6.

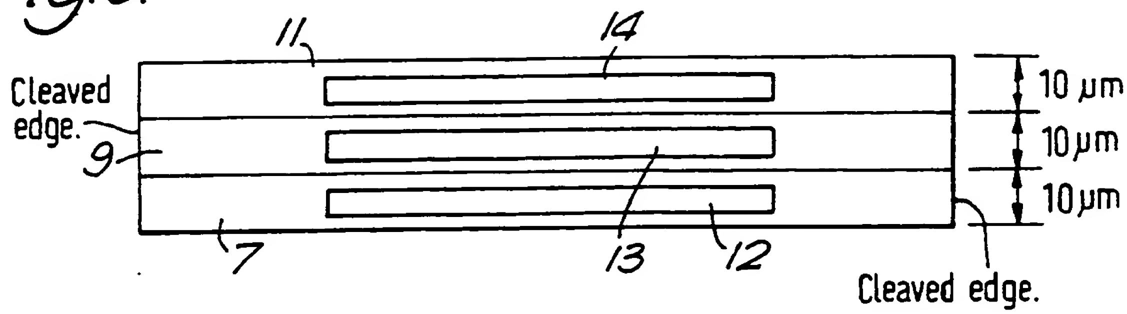

11
14
10 µm
Cleaved edge.
10µm
9
10µm
7
13
12
Cleaved edge.

Fig. 7.

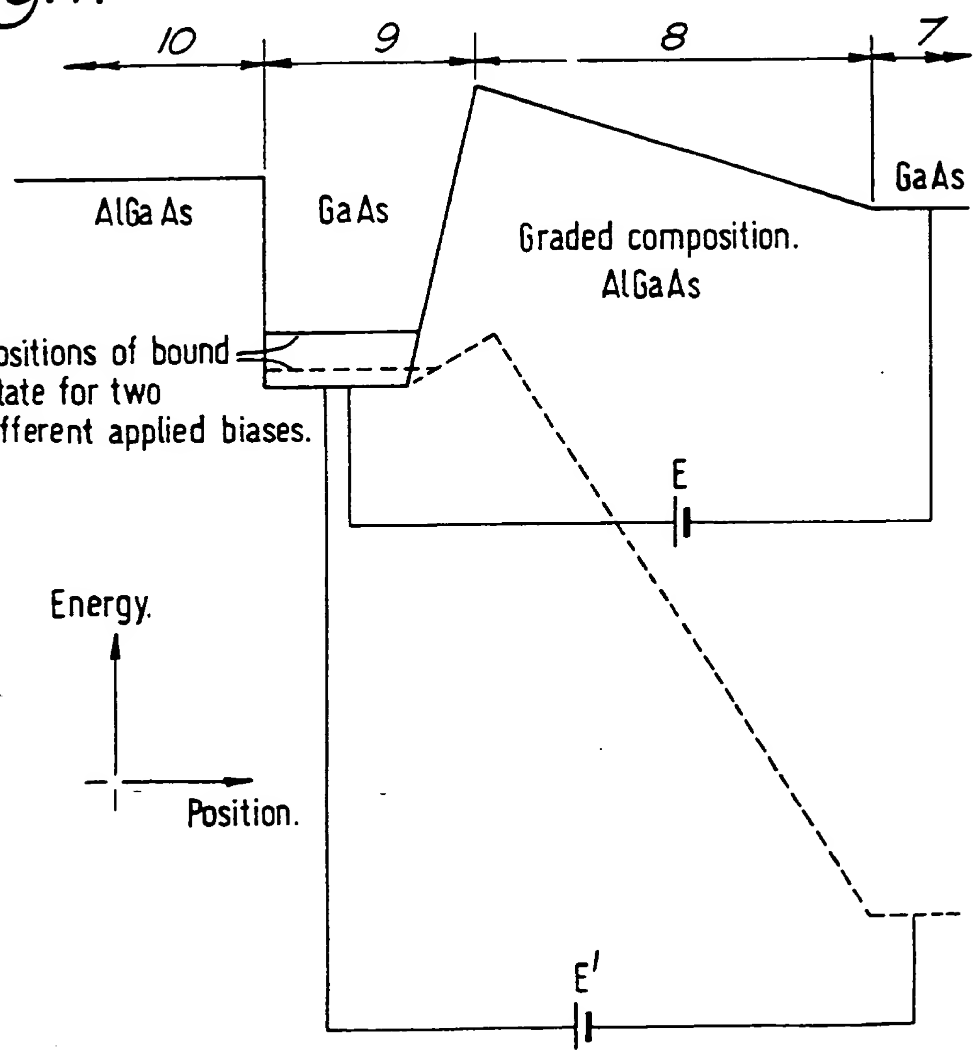

10
9
8
7
AlGa As
Ga As
Ga As
Graded composition.
AlGaAs
Positions of bound state for two different applied biases.
E
Energy.
Position.
E'

Fig. 8.

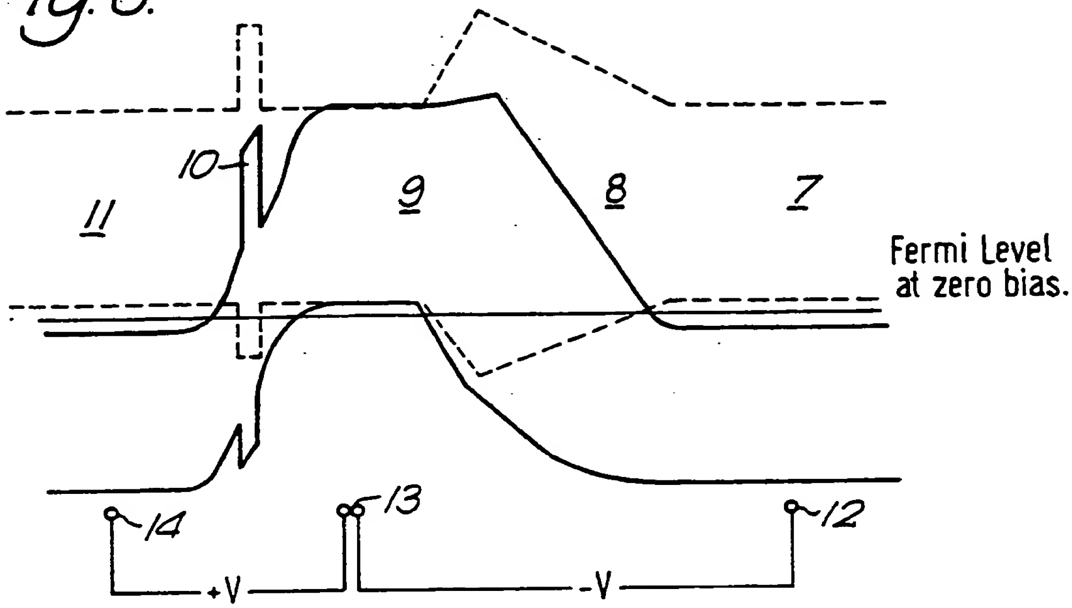

10
11
9
8
7
Fermi Level
at zero bias.
14
13
12
+V
-V

Fig. 9.

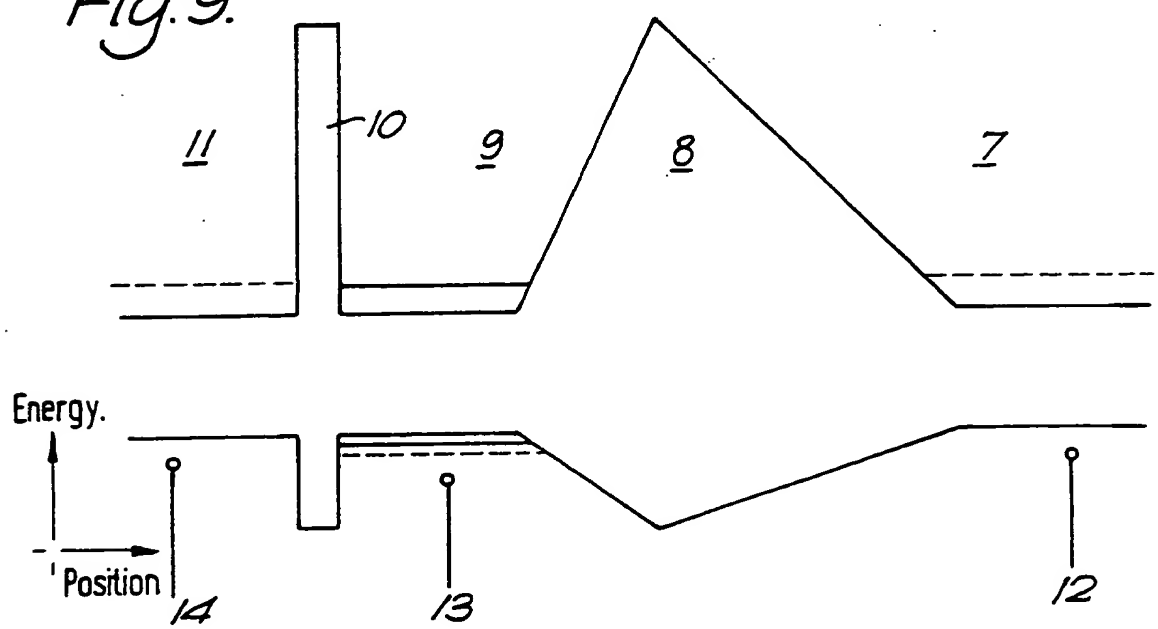

10
11
9
8
7
Energy.
Position
14
13
12

Fig.10.

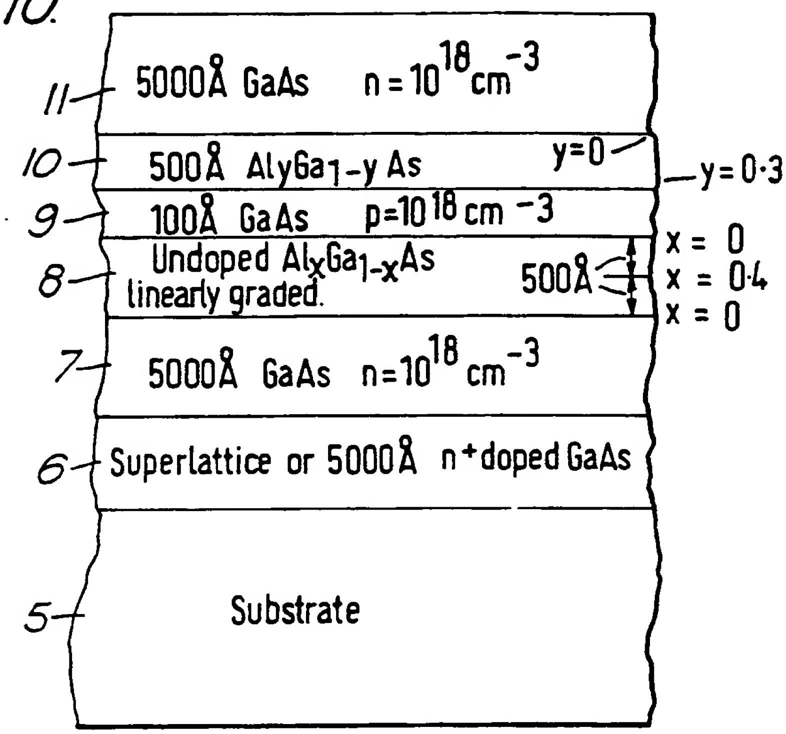
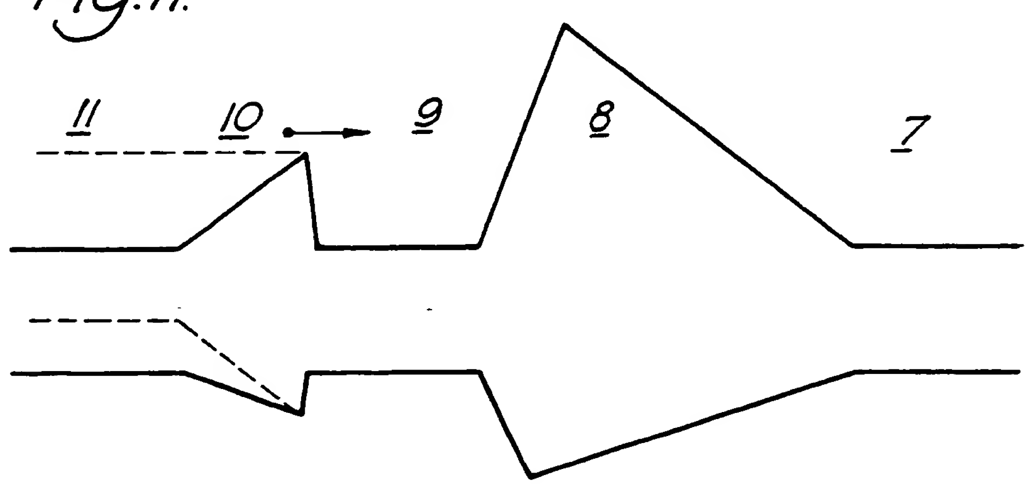

11
5000Å GaAs n = 10^18 cm^-3
10
500Å AlyGa1-y As
y=0
y=0·3
9
100Å GaAs p=10^18 cm^-3
8
Undoped AlxGa1-xAs linearly graded.
500Å
x = 0
x = 0·4
x = 0
7
5000Å GaAs n=10^18 cm^-3
6
Superlattice or 5000Å n+doped GaAs
5
Substrate

Fig.11.


11
10
9
8
7

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HRF/3389

Lasers

This invention relates to semiconductor laser devices, and particularly to quantum well semiconductor laser devices.

Conventional simple semiconductor lasers usually comprise a pn junction in a direct gap semiconductor material, i.e. a material in which an electron can transfer from the bottom of the conduction band to the top of the valence band giving rise to the emission of a photon. Figure 1 of the accompanying drawings is a graph showing energy/momentum curves related to the conduction and valence bands. It will be seen that the transfer takes place with zero change in momentum. An example of such a direct gap material is gallium arsenide.

Figure 2 illustrates, schematically, a mesa structure of a conventional semiconductor laser diode. The structure comprises an n-doped region 1, a p-doped region 2 and a recombination region 3 therebetween.

When a forward bias is applied to the pn junction from a d.c. source 4, electrons and holes may recombine in the region 3, each pair causing a photon of light to be emitted in the plane of the junction, with an energy equal to the energy band gap of the semiconductor material. If the mesa is suitably prepared, it can act as a Fabry-Perot cavity, which traps the emitted light. That light will then generate stimulated light emission and, under suitable conditions,

lasing occurs. The device therefore acts as a laser which produces light with an energy corresponding to the band gap, which is determined solely by the particular semiconductor material and cannot be changed for that material.

It is clearly a limitation of such devices that for a given material the device can lase only at a predetermined energy, and hence only at a predetermined frequency.

More recently, quantum well lasers have been developed which improve this situation to some extent. In these structures, a narrow region of a suitable material, such as GaAs, is grown between two layers of, for example, AlGaAs. The energy band diagram for such a device is shown in Figure 3 of the drawings. The GaAs layer forms a quantum well which has bound states in both the valence band and the conduction band, the energies of which, relative to the GaAs conduction band are determined by the thickness of the well. The energy gap between these bound states in turn determines the energy of the laser light output.

An advantage of the quantum well device over the simple laser device described previously is that a quantum well laser may be designed to generate light at a selected frequency which is determined by the thickness of the qunatum well and not solely by the semiconductor material used. Nevertheless, the device still suffers from a disadvantage, in that the quantum well thickness is determined during fabrication of the device, and, once that is done, the energy, and hence the frequency, of the light is fixed and cannot thereafter be changed.

It is an object of the present invention to provide a laser device of the quantum well type, the frequency of the light output of which can be adjusted, in use, by application of a bias voltage to the device.

According to the invention, there is provided a light-emitting device, comprising a first structure exhibiting a quantum well the energies of bound states in which are variable by application of a first voltage between regions of said first structure; and a second structure responsive to a second voltage

applied thereto to cause injection of electrons into the quantum well, whereby recombination of electrons and holes in the quantum well produces photons the energy of which is dependent upon said first voltage.

Embodiments of the invention will now described, by way of example, with reference to the accompanying drawings, in which

Figure 1 illustrates energy/momentum curves for a direct gap semiconductor material, as described above,

Figure 2 illustrates, schematically, a mesa structure for a conventional semiconductor laser diode, as described above,

Figure 3 illustrates energy band profiles for a known quantum well laser of the GaAs type, as described above,

Figure 4 illustrates, schematically, an example of a layer structure suitable for forming a tunable quantum well laser device in accordance with the invention,

Figures 5 and 6 are schematic pictorial end and plan views, respectively, of a mesa structure comprising the layers of Figure 4.

Figure 7 illustrates, schematically, the conduction band minimum energy profile of the device of Figures, 4, 5 and 6,

Figure 8 illustrates, schematically, the conduction band minimum energy and the valence band maximum energy profiles for the device of Figures 4, 5 and 6,

Figure 9 illustrates, schematically, variations in the band profiles due to various bias voltages applied to the device of Figures 4, 5, and 6,

Figure 10 illustrates, schematically, the layer structure of an alternative form of quantum well laser device in accordance with the invention; and

Figure 11 illustrates, schematically, the energy band profiles of the structure of Figure 10.

Referring to Figure 4, an example of a suitable layer structure for a laser device in accordance with the invention comprises a substrate 5 of, for example, GaAs on which is deposited a buffer layer 6, which may be a superlattice or may be an n^+ doped GaAs layer of, for example, 5000Å thickness. On the layer 6 is deposited a layer 7 of n doped GaAs of, say 5000Å thickness and having a doping

level of $10^{18}cm^{-3}$. A layer 8 of undoped material of the form $Al_xGa_{1-x}As$ is desposited over the layer 7, wherein x increases linearly from zero adjacent to the layer 7 up to 0.4 at a layer thickness of, say, 500Å and then decreases linearly to zero over a further thickness of, say 500Å. A layer 9 of p doped GaAs of, say, 100A thickness is formed over the layer 8, the doping density being, say, $10^{18}cm^{-3}$. A layer 10 of undoped AlAs of some 50Å thickness is deposited over the layer 10, and an n doped GaAs layer 11 of, say, 5000Å thickness and doping density of, say, $10^{18}cm^{-3}$ is deposited over the layer 10. All of the layers 6-11 may be deposited by molecular beam epitaxy.

After deposition of the layers, the structure is subjected to a selective etching process so that a section of the layers 11 and 10 is etched away, the etching continuing partially into the layer 9. A section of the layers 9 and 8 is then etched away, revealing part of the layer 7. A stepped structure as shown in Figures 5 and 6 is thereby produced, the steps being, say 10μm wide. Metal contact layers 12, 13 and 14 are then deposited on the layers 7, 9 and 11, respectively, to provide ohmic contacts.

The laser device according to the invention is, therefore, a three-terminal device, somewhat similar to a transistor.

In use of the device, a dc source 15 is connected to bias the layer 7 negatively relative to the layer 9, and a dc source 16 biases the layer 11 positively relative to the layer 9. The conduction band minimum energy profile for the device described above is shown schematically in Figure 7. The full line represents the profile for a first bias voltage between the layers 7 and 9, and the dotted line represents the profile for a larger negative bias voltage at the layer 7. It will be seen that the profile comprises a constant energy level for the GaAs layer 7, a triangular profile for the graded AlGaAs layer 8, a quantum well at the GaAs layer 9, and a constant energy level for the AlGaAs layer 10. If the bias voltage is increased to E', the profile of the graded layer 8 will tilt downwards as indicated by the dotted line. The bound state in the quantum well has

different energy levels for the two different bias voltages. Other degrees of tilting and other bound state energy levels will result from other values of bias voltage.

As will be apparent from the above description of the layer structure, the layers or regions 7, 9 and 11 are direct gap semiconductor regions which are heavily doped n, p and n, respectively. The region 10 is a semiconductor region forming heterojunctions with the regions 9 and 11. It comprises a material which forms barriers at the heterojunction in both the valence and conduction bands. The region 8 is an undoped region, the profile of the material composition of which varies in such a way that a triangular barrier is formed between the regions 7 and 9 in both the valence and conduction band. In each case the opposite conductivity doping could be effected.

The band profiles in zero bias are shown in full lines in Figure 8. In order to realise the band profile shown in Figure 9, and as shown in dotted lines in Figure 8, the bias voltages mentioned above must be applied to the regions 7, 9 and 11. As the voltage applied between the regions 9 and 11 is increased, electrons will tunnel through the barrier constituted by the region 10, which separates the regions 9 and 11. Together the regions 11 and 10 thereby constitute means for injecting electrons into the region 9 in a controllable manner.

The flow of electrons and holes in the layers 11 and 9, respectively, is represented by arrows in Figure 5. Recombination of the electron/hole pairs occurs in the layer 9, and light is emitted, as a result, from the edge of that layer.

The basis of the present invention lies in varying the bound state energies in the region 9 where lasing occurs, by varying the voltage applied between the regions 9 and 7. This has the effect of varying the potential profile through the device and, hence, the energies of the bound states in the region 9.

The necessary injection of electrons could be effected by other types of electron injections. For example, a layer structure is shown in Figure 10 in which a triangular barrier is formed at the layer 10. The structure of the layers 6-9 and 11 can be the same as

in Figure 4, but the layer 10 comprises a layer of $Al_xGa_{1-x}As$ of, say, 500Å thickness, in which x varies from, say, 0.3 adjacent the layer 9 down to zero adjacent the layer 11. The corresponding energy band profiles for such a structure is shown in Figure 11.

In a device in accordance with the invention, therefore, by growing a suitable semiconductor structure the energies of the bound states in a quantum well can be controlled by varying an externally-applied potential difference. By doping the quantum well layer so that it is p type and injecting electrons by varying a second externally-applied potential difference, electrons and holes will recombine, emitting a photon of light. The energy of this photon is equal to the difference between the electron and hole bound state energies. This energy may be controlled by varying the external voltage as described above. In a suitably prepared mesa such photon emission processes may be used to generate lasing via stimulated emission.

From Planck's law,

$$E = h\nu \text{ or } \nu = \frac{E}{h}$$

where ν is the frequency of the emitted light,
E is the energy of the photon,
and h is Planck's constant.

Hence, by varying the energy E in the above manner, the frequency of the laser output can be varied.

It will be apparent that the output frequency can be varied by varying the applied voltage at any time in use of the device, and that the frequency is not determined solely by the thickness of the layer providing the quantum well.

CLAIMS

1. A light emitting device, comprising a first structure exhibiting a quantum well the energies of bound states in which are variable by application of a first voltage between regions of said first structure; and a second structure responsive to a second voltage applied thereto to cause injection of electrons into the quantum well, whereby recombination of electrons and holes in the quantum well produces photons the energy of which is dependent upon said first voltage.

2. A device as claimed in Claim 1, wherein said first structure comprises first and second regions of a direct-gap semiconductor material, the two regions being of opposite conductivity types, and a third region of a semiconductor material which exhibits an energy gap of triangular shape forming a barrier between said first and second regions; and wherein the quantum well is formed in said second region.

3. A device as claimed in Claim 2, wherein said second structure comprises a fourth region of the same semiconductor material as said first and second regions, and of the opposite conductivity type to said second region; and a fifth region forming an energy barrier between said second and fourth regions through which electrons tunnel into said second region in response to said second voltage.

4. A device as claimed in Claim 3,wherein said fifth region forms an energy barrier of triangular profile.

5. A device as claimed in Claim 2, wherein said first and second regions are formed of GaAs, and said third region is formed of $Al_xGa_{1-x}As$, where x increases from zero to about 0.4 and then reduces to zero through the thickness of the region.

6. A device as claimed in Claim 3, wherein said first, second and fourth regions are formed of GaAs, said third region is formed of $Al_xGa_{1-x}As$, where x increases from zero to about 0.4 and then reduces to zero through the thickness of the region; and said fifth region is formed of AlAs.

7. A device as claimed in Claim 4, wherein said first, second and fourth regions are formed of GaAs, said third region is formed of

$Al_xGa_{1-x}As$, where x increases from zero to about 0.4 and then reduces to zero through the thickness of the region; and said fifth r gion is formed of $Al_yGa_{1-y}As$, where y decreases through the thickness of the region from about 0.3 adjacent said second region to zero adjacent said fourth region.

8. A device as claimed in Claim 3, wherein a portion of each of said second to fifth regions is removed to reveal a portion of said first region, and a portion of each of said fourth and fifth regions is removed to reveal a portion of said second region; and wherein ohmic contacts are provided on the revealed portions of said first and second regions and on the remaining part of the fourth region, whereby said voltages can be applied thereto.

9. A light-emitting device substantially as hereinbefore described with reference to Figures 4 to 11 of the accompanying drawings.

10. A laser device including a light-emitting device as claimed in any preceding claim.

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